

Cluster Cosmology at a Crossroads: Neutrino Masses

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ABSTRACT

Galaxy clusters — in combination with CMB and BAO data — can provide precise constraints on the sum of neutrino masses. However, these constraints depend on the calibration of the mass–observable relation. For instance, the mass calibration employed in Planck Collaboration (2011a,b) rules out the minimal 6-parameter Λ CDM model at 3.7σ , and implies a sum of neutrino masses $\sum m_\nu = 0.39 \pm 0.10$. By contrast, the mass calibration favored by Rozo et al. (2012b) from a self-consistent analysis of X-ray, SZ, and optical scaling relations is consistent with a minimal flat Λ CDM model with no massive neutrinos (1.7σ), and is a better fit to additional data (e.g. H_0). We discuss these results in light of the most recent SPT and ACT analyses, and the implications of our results on the current mild “tension” ($< 2\sigma$) between CMB and BAO+ H_0 data.

Key words: cosmology: clusters

1 INTRODUCTION

Galaxy clusters provide an important complementary probe to the Cosmic Microwave Background (CMB) and geometric probes like Baryon Acoustic Oscillations (BAO). Specifically, clusters provide precise estimates of the so called cluster normalization condition, $\sigma_8 \Omega_m^\gamma$, where $\gamma \approx 0.5$ (see Allen et al. 2011; Weinberg et al. 2012, for a general review of cluster cosmology). While the CMB provides an accurate measurement of the amplitude of the power spectrum at the epoch of last scattering, the corresponding constraint on the cluster normalization condition can be highly uncertain due to the extrapolation from $z \approx 1200$ to $z \approx 0$. This uncertainty is primarily dominated by the impact of Ω_m on the growth function, but also depends on additional cosmological parameters such as curvature, the dark energy equation-of-state, and, most relevant for our purposes, neutrino masses. By directly measuring the amplitude of matter fluctuations in the low redshift universe and comparing to the range of theoretical predictions from CMB+BAO data, galaxy clusters allow us to improve cosmological constraints on these parameters over and above the CMB+BAO only results (e.g. Burenin & Vikhlinin 2012; Mantz et al. 2010; Reid et al. 2010).

However, the cosmological constraints from galaxy clusters are critically dependent on our ability to estimate

cluster masses. We illustrate this basic argument using the results of Vikhlinin et al. (2009b, hereafter V09), highlighting how the constraints on neutrino mass depend on the adopted cluster mass calibration. In particular, we consider two additional mass calibrations, that adopted in Planck Collaboration (2011a,b) and that of Rozo et al. (2012b). We then connect these arguments to the recent results from SPT (Hou et al. 2012) and ACT (Sievers et al. 2013; Hasselfield et al. 2013), with some emphasis on the mild tension ($< 2\sigma$) between CMB and BAO data in the current analyses.

All of our results are computed using importance sampling of the WMAP9 chains (Hinshaw et al. 2012). The likelihood distributions are computed using a Kernel Density Estimator (KDE), where each point is assigned the weight reported in the WMAP9 chains. When adding galaxy clusters, we rely on the fact that low-redshift galaxy clusters only constrain a specific combination of cosmological parameters, namely $\sigma_8 \Omega_m^\gamma$ where $\gamma \approx 0.5$, with this constraint being essentially independent of the remaining cosmological parameters. Consequently, galaxy clusters modify the weight w_i for each point in the WMAP9 chains via

$$w_{i,cl} = w_i \exp \left[-\frac{1}{2} \frac{(s_{8,i} - s_{8,prior})^2}{\sigma_s^2} \right] \quad (1)$$

where w_i is the original weight, and $s_8 = \sigma_8 \Omega_m^\gamma$ is the relevant cluster normalization condition. All upper limits on neutrino masses are 95% confidence. Constraints of the form $\sum m_\nu = X_{-b}^{+a}$ imply X is the maximum likelihood point, and a and b define the 68% confidence contour. All constraints are reported after marginalizing over the remaining model parameters. For a general review of cosmological bounds on neutrino masses, we refer the reader to Lesgourgues & Pastor (2012). Recent reviews on cluster cosmology can be found in Weinberg et al. (2012); Allen et al. (2011).

Throughout, a minimal Λ CDM model references a flat Λ CDM models with only 6 free parameters: the amplitude of the primordial power spectrum fluctuations A_s , the tilt of the primordial power spectrum n_s , the matter density Ω_m , the hubble parameter h , the angular scale of the sound horizon at last scattering θ_s , and the optical depth to the surface of last scattering τ .

2 HOW GALAXY CLUSTERS INTERACT WITH CMB+BAO CONSTRAINTS

V09 provides a precise constraint on the quantity $s_8 \equiv \sigma_8(\Omega_m/0.25)^{0.47} = 0.813 \pm 0.013$. The error bar is statistical errors only: in the spirit of the V09 analysis, we consider systematic shifts in the mass scale independently. By comparison, the uncertainty from WMAP9 data only (Hinshaw et al. 2012) in a minimal Λ CDM model is significantly larger, $s_8 = 0.866 \pm 0.058$. Note that because s_8 was defined using $\Omega_m = 0.25$ as a reference value, the fact that $\Omega_m \approx 0.28$ from WMAP9 data implies that the quoted s_8 value is significantly higher than the σ_8 value derived from WMAP9, $\sigma_8 = 0.82$. The uncertainty in s_8 can be reduced with an independent probe of Ω_m , or, since WMAP9 constrains $\Omega_m h^2$, a measurement of h . The most significant improvement occurs when one adds BAO information (based on the analyses in Beutler et al. 2011; Padmanabhan et al. 2012; Anderson et al. 2012; Blake et al. 2012), which results in $s_8 = 0.898 \pm 0.029$ after marginalizing over all other parameters. This value is borderline consistent with the V09 result (2.7σ).

One can decrease the modest tension between WMAP9+BAO and V09 by allowing for dynamical dark energy or curvature. However, the single extension that leads to the largest improvement is allowing for non-zero neutrino masses. Because neutrinos can escape their initial density peak, massive neutrinos effectively smear out a fraction of the mass over the neutrino free streaming scale, leading to a reduced value of the predicted amplitude of matter fluctuations at $z = 0$. In this extension of the minimal flat Λ CDM model, the WMAP9+BAO prediction for s_8 after marginalizing over all other parameters is $s_8 = 0.828 \pm 0.053$, in excellent agreement with the V09 result (0.2σ offset).

The WMAP9+BAO only constraint on the sum of neutrino masses is $\sum m_\nu \leq 0.58$. As shown by the red and yellow contours in Figure 1, this constraint is strongly degenerate with the cluster normalization condition, a degeneracy that persists even if one adds SPT, ACT, and H_0

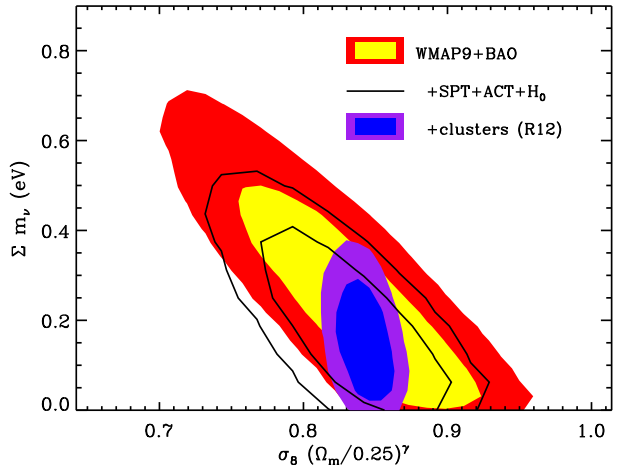


Figure 1. 68% and 95% confidence contours in the $s_8 - \sum m_\nu$ plane, where $s_8 = \sigma_8(\Omega_m/0.25)^{0.47}$. Red/yellow ellipses are from WMAP9+BAO data only, while the solid curves add SPT, ACT, and H_0 data as in Hinshaw et al. (2012). The blue/purple contours show the impact of adding galaxy clusters with the Rozo et al. (2012b) mass calibration.

data (solid line ellipses). The origin of this degeneracy is clear: the CMB constrains the amplitude of matter fluctuations at last scattering. Massive neutrinos take part of the initial mass fluctuations and “spread it out” over the free-streaming scale, leading to a smoother Universe (lower s_8). The more mass one spreads — i.e. the more massive the neutrinos are — the smoother the late Universe is, leading to the observed anti-correlation.

Adding galaxy clusters breaks this degeneracy. Using the V09 constraints we find

$$\sum m_\nu = 0.31_{-0.11}^{+0.10} \text{ eV} \quad \text{WMAP9+BAO+Cl (V09)} \quad (2)$$

Note that the purple/blue contours in Figure 1 are not those obtained with the original V09 cluster normalization condition, reflecting instead the results obtained using the Rozo et al. (2012b) mass calibration. We discuss this result in more detail below. For a more detailed discussion of the V09 results using WMAP7 data and BAO constraints pre-BOSS, see Burenin & Vikhlinin (2012).

3 THE ROLE OF MASS CALIBRATION

The sensitivity of the cluster normalization condition to the mass calibration of galaxy clusters is intuitively obvious: as one increases the mass assigned to galaxy clusters, the resulting cosmological constraints result in a more inhomogeneous Universe (higher σ_8) with higher matter density. Thus, higher cluster masses result in higher cluster normalization conditions. Because of the strong $\sum m_\nu - s_8$ degeneracy in the WMAP9+BAO data, it follows that cluster mass calibration can have a dramatic impact on the recovered neutrino mass.

We illustrate the importance of cluster masses

Table 1. Mass calibration offset $\Delta \ln M$ relative to Vikhlinin et al. (V09 2009a) for the cluster mass scale employed in Planck Collaboration (P11 2011b) and Rozo et al. (R12 2012b), and the corresponding cluster mass normalization condition s_8 .

Reference	$\Delta \ln M$	$s_8 = \sigma_8(\Omega_m/0.25)^\gamma$
V09	—	0.813
P11	-0.12 ± 0.02	0.781
R12	0.11 ± 0.04	0.842

on neutrino mass constraints by considering how the WMAP9+BAO+Cl constraint change as we shift the mass calibration away from that employed in V09. To compute the cluster normalization condition for an arbitrary mass calibration, we rely on V09, who shows that systematically shifting the mass of all galaxy clusters by $\pm 9\%$ shifts the corresponding s_8 value by ± 0.024 . Consequently, for small mass shifts $\Delta \ln M$ is the mass calibration offset relative to V09, we can approximate the s_8 dependence on cluster mass calibration via

$$s_8 = s_{8,V09} + 0.024 \frac{\Delta \ln M}{0.09}. \quad (3)$$

The left panel in Figure 2 shows the posterior distribution for $\sum m_\nu$ for a combined WMAP9+BAO+Cl analysis using a variety of different mass calibrations. In addition to the original V09 mass calibration (orange line), we consider the mass calibration of Arnaud et al. (2010) as employed in Planck Collaboration (P11 2011a,b, red curve), and that advocated for in Rozo et al. (2012b, blue curve, R12). The mass offset $\Delta \ln M$ of the various mass calibrations is defined as the difference in the log-mass between the various works, averaged over all galaxy clusters. So, for instance, the mass shift $\Delta \ln M$ between P11 and V09 was computed by selecting all galaxy clusters in common to these two cluster samples, computing the difference in the log-mass, and then averaging over all such clusters (see Rozo et al. 2012a, for details). A similar analysis for the R12 mass calibration is done in Rozo et al. (2012b). The mass offsets and the corresponding cluster normalization conditions are summarized in Table 1.

The corresponding constraints on the sum of the neutrino masses for these mass calibrations are

$$\sum m_\nu = 0.39 \pm 0.10 \text{ eV} \quad \text{WMAP9+BAO+Cl (P11)} \quad (4)$$

and

$$\sum m_\nu = 0.21 \pm 0.11 \text{ eV} \quad \text{WMAP9+BAO+Cl (R12)}. \quad (5)$$

Alternatively, we can also directly determine whether the value of s_8 predicted from the combination of WMAP9+BAO data in a minimal Λ CDM model ($\sum m_\nu = 0$), and compare it to the observational constraints from galaxy clusters as a test of this minimal cosmological model. We find that the Planck Collaboration (2011a,b) mass calibration rules out the minimal flat Λ CDM model at 3.7σ , whereas the Rozo et al. (R12, 2012b) mass calibration is consistent with a minimal Λ CDM model at the 1.7σ level.

Both results were expected a priori based on the discussion in Rozo et al. (2012b), where we showed that the X-ray luminosity function and the Planck Collaboration (2011a,b) mass calibration were inconsistent with WMAP7+BAO data for a minimal Λ CDM model. Note, however, that the abundance tests in Rozo et al. (2012b) were performed as an *a posteriori* check on the proposed solution to the original Planck–maxBCG discrepancy, i.e. this mass calibration was not tuned by fitting X-ray and optical abundance data.

4 THE IMPORTANCE OF CLUSTER MULTI-WAVELENGTH MODELING

While mass calibration suffers from significant uncertainties (see Rozo et al. 2012a; Applegate et al. 2012, for a comparison of cluster masses from the literature), we note that multi-wavelength data can provide compelling evidence for favoring one set of mass calibrations over another. In particular, models that are inconsistent with any one aspect of a full multi-wavelength analysis should be rejected, unless additional presently-unknown systematics are identified.

Consider, for instance, the Planck–maxBCG discrepancy. Planck Collaboration (2011c) noted the observed SZ signal of maxBCG galaxy clusters was lower than predicted. Since, Sehgal et al. (2012) found ACT data to be in conflict with both the predicted SZ signal of maxBCG clusters, as well as the Planck measurements. Sehgal et al. (2012) finds that in order for cluster miscentering to account for these offsets one would require all the maxBCG clusters to be miscentered, with a uniform miscentering kernel extending out to $R = 1.5$ Mpc. However, this miscentering model is clearly ruled out by X-ray data (see Fig. 2 in Sehgal et al. 2012), which shows that the central galaxy of maxBCG clusters is most often coincident with the X-ray peak (see also Menanteau et al. 2013; von der Linden et al. 2012; Mahdavi et al. 2012; Song et al. 2012; Stott et al. 2012, and references therein). Moreover, a miscentering kernel this large would also have a dramatic impact on the weak lensing masses, further heightening the tension between Planck/ACT and maxBCG. We concur with Sehgal et al. (2012) that cluster miscentering cannot be the main explanation for the observed SZ offsets.

As a second example, Planck Collaboration (2011c) and Angulo et al. (2012) both noted the predicted SZ signal for maxBCG galaxy clusters obtained from the path $N_{200} \rightarrow L_X \rightarrow Y_{SZ}$ differed from the prediction obtained through the path $N_{200} \rightarrow M \rightarrow Y_{SZ}$. That is, the full set of X-ray, SZ, and optical cluster scaling relations that led to the Planck–maxBCG discrepancy was not internally self-consistent, a clear signal of systematic errors. A correct and fully self-consistent set of scaling relation must allow one to go from from any two scaling relations to a third and still arrive at the same predicted scaling relation.

As was demonstrated in Rozo et al. (2012b), lowering the optical mass estimates within its systematic errors while simultaneously increasing the X-ray mass estimates within its systematic errors results in an overall mass calibration that resolves the Planck–maxBCG discrepancy.

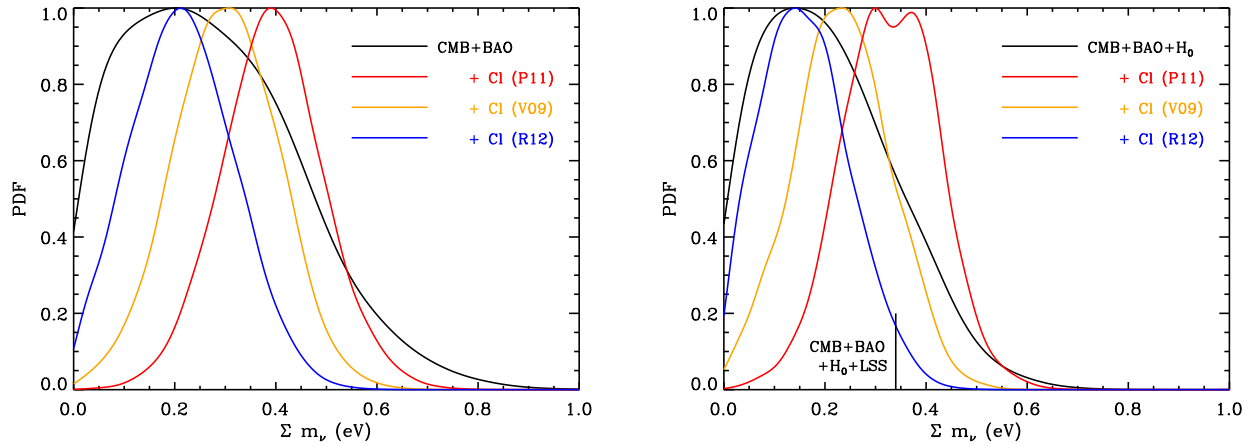


Figure 2. *Left panel:* Posterior for the sum of neutrino masses $\sum m_\nu$ for a variety of different analyses. The black curve is the WMAP9+BAO result from Hinshaw et al. (2012), while the red, purple, and blue curves show the posteriors after inclusion of the cluster normalization condition appropriate for the Planck Collaboration (2011a,b), Vikhlinin et al. (2009a), and Rozo et al. (2012b) mass calibrations. *Right panel:* As left panel, but starting with CMB+BAO+ H_0 constraints. Here, CMB refers to WMAP9+SPT+ACT data. The small vertical line at $\sum m_\nu = 0.34$ marks the 95% confidence upper limit derived using the galaxy correlation function from WigglyZ (Parkinson et al. 2012) and BOSS (Zhao et al. 2012).

ancy, fits all available X-ray and SZ data, and results in a self-consistent set of scaling relations. Moreover, this correctly reproduces optical and X-ray cluster abundances in a minimal Λ CDM model with WMAP7+BAO priors, it correctly predicts the thermal SZ power spectrum amplitude (Reichardt et al. 2011, e.g.), and the resulting masses are consistent with all published CLASH data available to date (Coe et al. 2012; Umetsu et al. 2012). Consequently, we believe there is strong motivation to prefer the mass calibration advocated in Rozo et al. (2012b). We now extend the implications of this mass normalization to a more general cosmological context.

5 THE ROLE OF EXTERNAL DATA

We consider the impact of adding small scale CMB data from SPT and ACT and external constraints on H_0 on our analysis. We again rely on the WMAP9 chains and importance sampling, and note that Hinshaw et al. (2012) have verified the internal consistency of these additional external data sets. The H_0 data is that of Riess et al. (2011), while the SPT and ACT data are from Keisler et al. (2011) and Das et al. (2011) respectively.

The right panel in Figure 2 shows the posterior on the sum of neutrino masses derived from the combination of CMB+BAO+ H_0 with galaxy clusters, where CMB includes WMAP9, SPT, and ACT data. The three colored curves correspond to the three mass normalization conditions we have discussed in this work: Planck Collaboration (P11- red curve, 2011a,b), Vikhlinin et al. (V09- orange curve, 2009a), and Rozo et al. (R12- blue curve, 2012b). Relative to the left panel, which does not include H_0 or small scale CMB data, all posteriors shift to the left, towards lower neutrino masses, and consistent with a higher mass calibration. When using

this full data set, the 95% confidence contour obtained with the Rozo et al. (2012b) mass calibration includes the point $\sum m_\nu = 0$, and the corresponding upper limit is

$$\sum m_\nu \leq 0.32 \text{ eV} \quad \text{CMB+BAO+}H_0\text{+Cl (R12)}. \quad (6)$$

Further adding supernovae data as in Hinshaw et al. (2012) has a modest impact on our results, slightly shifting the neutrino masses further towards $\sum m_\nu = 0$.

We can compare our results with those from galaxy correlation function measurements. The two most relevant constraints with spectroscopic galaxy samples are those from the WigglyZ (Parkinson et al. 2012) and BOSS experiments (Zhao et al. 2012), both of which find $\sum m_\nu \leq 0.34$ eV at the 95% CL. Thus, the observed galaxy correlation function also favors low neutrino masses and a high cluster normalization condition. We note the main systematic in these analyses is the impact of non-linearities in the matter power spectrum and the model for galaxy bias, both of which are expected to be well controlled, and are completely independent of mass calibration systematics.

We now turn to the recent SPT and ACT results. Starting with ACT, their combined WMAP7+ACT+BAO analysis does not lead to a detection of neutrino masses (Sievers et al. 2013). Adding ACT cluster abundances relying on the dynamical mass calibration of Sifon et al. (2012) is also consistent with zero neutrino mass (Hasselfield et al. 2013). From Table 1 in this last work, we conclude the (Sifon et al. 2012) mass calibration is $\approx 17\%$ higher than that in (Planck Collaboration 2011a,b). Their posterior from the cosmological analysis is higher still, $\approx 27\%$. By comparison, the Rozo et al. (2012b) mass calibration is $\approx 21\%$ higher than that in Planck Collaboration (2011a,b).

Thus, it is not surprising that the ACT cluster analysis does not lead to a detection of neutrino masses.¹

Turning to SPT, Hou et al. (2012) quote a 3σ detection of neutrino mass, with $\sum m_\nu = 0.32 \pm 0.11$ eV, including galaxy clusters. The cluster constraint from SPT relies on the V09 cluster mass normalization (Benson et al. 2011), for which we found $\sum m_\nu = 0.31^{+0.10}_{-0.11}$ eV using WMAP9+BAO+clusters, in perfect agreement with the SPT result. In this sense our analysis are consistent, and lowering the mass calibration of SPT clusters should lead to a reduction of the recovered neutrino masses.

There is, however, one aspect of the Hou et al. (2012) results that may appear to contradict the discussion in this work. Specifically, Hou et al. (2012) marginalize over the systematic uncertainty in mass calibration quoted in V09, finding that the posterior in the neutrino masses is essentially independent of the width of this prior, and contrary to what one might expect given our discussion. There is, however, no inconsistency. This is best understood using Figure 1. Clusters provide a tight constraint on the cluster normalization condition s_8 , which is degenerate with $\sum m_\nu$ in the CMB+BAO+ H_0 data set. As long as the constraint on s_8 is modest, clusters simply “pick out” an s_8 value, and the posterior on the neutrino mass only reflects the CMB+BAO+ H_0 data with an effective infinitely sharp prior on s_8 , so the posterior on $\sum m_\nu$ is insensitive to the precise width of the s_8 prior (i.e. the mass calibration uncertainty). Nevertheless, shifting the central value s_8 still slides the cosmological constraints along the $\sum m_\nu$ - s_8 degeneracy. In short, the recovered neutrino masses are robust to changes in the width of the s_8 (or mass calibration) prior, but not to shifts in the corresponding central value.

6 ON THE CMB AND BAO+ H_0 TENSION

As emphasized by Hou et al. (2012), one critical driving force behind the SPT detection of neutrino masses is the mild tension ($\leq 2\sigma$) between CMB and BAO+ H_0 data in a minimal Λ CDM cosmology. We follow Hou et al. (2012) and illustrate this tension in Figure 3 by comparing current CMB constraints on $r_s/D_V(0.57)$ and H_0 for a minimal Λ CDM model to the BAO measurements of Anderson et al. (2012) and H_0 measurements from Riess et al. (2011). Here, r_s is the comoving sound horizon at decoupling, and

$$D_V(z) = [z(1+z)^2 D_A^2(z) c H^{-1}(z)]^{1/3} \quad (7)$$

where D_A is the angular diameter distance.

Consider now how galaxy clusters affect this discussion. The solid and dashed ellipses in Figure 3 show the 95% confidence contours obtained when adding a cluster normalization condition prior to the CMB data, using the Rozo et al.

¹ It is worth nothing that unlike the SPT analysis, ACT does not see any evidence of neutrino mass from a CMB+BAO only analysis— compare Fig. 8 in Sievers et al. (2013) with Fig. 9 in Hou et al. (2012). Given that the two data sets are consistent (Calabrese et al. 2013), this suggests there may be a subtle difference between the two analyses pipelines.

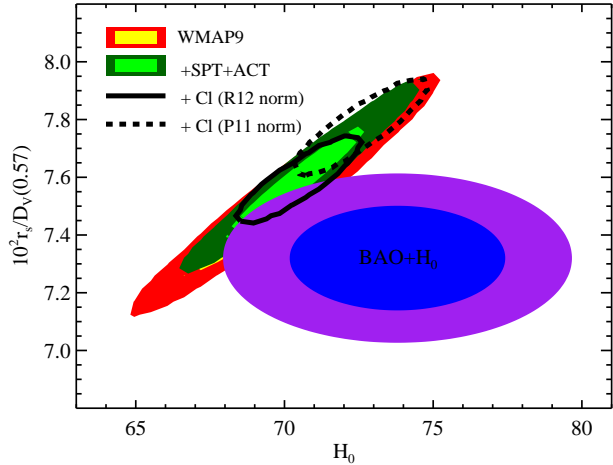


Figure 3. Comparison of the 68% and 95% likelihood contours in the $r_s/D_V(0.57)$ - H_0 plane from various data sets assuming a minimal Λ CDM model, as labelled. The modest tension between CMB and BAO+ H_0 data increases when adding galaxy clusters with a low cluster mass normalization (e.g. Planck Collaboration 2011a,b). The Rozo et al. (2012b) mass normalization shrinks the CMB contours around the CMB and BAO+ H_0 overlap region.

(2012b) and Planck Collaboration (2011a,b) mass calibrations respectively. Galaxy clusters tighten the confidence regions in the $r_s/D_V(0.57)$ - H_0 plane, but that the choice of mass calibration shifts the posterior for the combined data sets along the CMB degeneracy curve. Of the 3 mass calibration we consider here, the Rozo et al. (2012b) mass calibration falls closest to the intersection of the CMB and BAO+ H_0 data; In such a scenario, the current “tension” could easily reflect a statistical fluctuation, in which case the various contours will likely shift towards each other as the uncertainties in the measurements continue to decrease.

By contrast, a low mass calibration such as that of Planck Collaboration (2011a,b) heightens the existing tension between CMB and BAO+ H_0 data. Moreover, while non-zero neutrino masses can reconcile this data with galaxy clusters, this new degree of freedom does not help alleviate the tension between the CMB and BAO+ H_0 data sets. Indeed, this tension is most effectively alleviated by increasing the effective number of neutrino species (not shown, but see Figure 3 in Hou et al. 2012). Since in this scenario our minimal Λ CDM model is already ruled out, there is really nothing “pulling” the BAO+ H_0 and CMB contours towards better agreement, in which case the tension between these data sets is likely to increase as the error bars decrease. If so, we should expect the evidence for massive neutrinos and a non-standard number of neutrino species to become compelling in the near future. Indeed, Burenin (2013) — a paper that appeared on the archive as we were finishing this work — argues for such a detection on the basis of current CMB+BAO+ H_0 and cluster data from V09.

7 SUMMARY AND DISCUSSION

Galaxy clusters are the key piece of data required to place tight cosmological constraints on the sum of the neutrino masses, with the resulting constraints being critically sensitive to the adopted mass calibration. We have noted that the self-consistency of optical, X-ray, and SZ scaling relations favor a high mass calibration, which helps reconcile CMB and BAO+ H_0 data in a minimal Λ CDM cosmological model, and allows us to place an upper limit on the sum of the neutrino masses, $\sum m_\nu \leq 0.32$ (95% CL). This constraint is nearly identical to that derived from CMB+BAO+ H_0 data combined with measurements of the galaxy power spectrum. By contrast, a lower mass calibration rules out the minimal Λ CDM model, and necessitates a non-zero neutrino mass.

This picture leaves us with an interesting dichotomy: the Rozo et al. (2012b) mass calibration suggests that the slight tension in the CMB and BAO+ H_0 data sets will likely decrease as error bars decrease. Conversely, should the low mass calibration of Planck Collaboration (2011a,b) be correct, the tension in the CMB and BAO+ H_0 data is at least in part due to a breakdown of the minimal Λ CDM model. In that case, this tension is likely to increase with decreasing errors, requiring both a non-zero neutrino mass and a non-minimal effective number of neutrino species. The Vikhlinin et al. (2009a) mass calibration falls somewhere in between, showing evidence for massive neutrinos at 2.7σ , and also favoring a high N_{eff} (Burenin 2013).

In short, it is clear that the combination of improved BOSS constraints and Planck data will provide an important test of the various cluster mass normalizations advocated for in the literature. From the point of view of internal self-consistency of X-ray, SZ, and optical data, we note that should the mass calibration advocated in Rozo et al. (2012b) be ruled out, then the existing X-ray, SZ, and optical data will be in tension once again. In this case, the resolution of the tension will likely require the identification of an additional, currently-unknown systematic in at least one of these data sets. Note too that because current X-ray mass calibrations assume no hydrostatic bias, it will also become important to understand why hydrodynamical simulations generically predict $\approx 10\% - 30\%$ hydrostatic biases (e.g. Nagai et al. 2007; Lau et al. 2009; Battaglia et al. 2011; Nelson et al. 2011; Rasia et al. 2012; Suto et al. 2013). Whatever the case may be, we find it beautifully ironic that the key systematic in our ability to weigh ≈ 0.1 eV neutrinos is our ability to weigh $\approx 10^{14} - 10^{15} M_\odot$ objects.

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